

LETTER TO THE EDITOR

Enhanced dielectronic recombination of lithium-like Ti^{19+} ions in external $\mathbf{E} \times \mathbf{B}$ fields

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Abstract.

Dielectronic recombination(DR) of lithium-like $\text{Ti}^{19+}(1s^22s)$ ions via $2s \rightarrow 2p$ core excitations has been measured at the Heidelberg heavy ion storage ring TSR. We find that not only external electric fields ($0 \leq E_y \leq 280$ V/cm) but also crossed magnetic fields ($30 \text{ mT} \leq B_z \leq 80 \text{ mT}$) influence the DR via high- n $2p_j n\ell$ -Rydberg resonances. This result confirms our previous finding for isoelectronic Cl^{14+} ions [Bartsch T *et al*, *Phys. Rev. Lett.* **82**, 3779 (1999)] that experimentally established the sensitivity of DR to $\mathbf{E} \times \mathbf{B}$ fields. In the present investigation the larger $2p_{1/2} - 2p_{3/2}$ fine structure splitting of Ti^{19+} allowed us to study separately the influence of external fields via the two series of Rydberg DR resonances attached to the $2s \rightarrow 2p_{1/2}$ and $2s \rightarrow 2p_{3/2}$ excitations of the Li-like core, extracting initial slopes and saturation fields of the enhancement. We find that for $E_y \gtrsim 80$ V/cm the field induced enhancement is about 1.8 times stronger for the $2p_{3/2}$ series than for the $2p_{1/2}$ series.

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Dielectronic recombination (DR) is a fundamental electron-ion collision process well known to be important in astrophysical and fusion plasmas (Dubau and Volonté 1980). It proceeds in two steps

$$e^- + A^{q+} \rightarrow [A^{(q-1)+}]^{**} \rightarrow A^{(q-1)+} + h\nu \quad (1)$$

where in the first step the initially free electron is captured into a bound state $n\ell$ of the ion with simultaneous excitation of a core electron. This dielectronic capture (DC, time inverse of autoionization) can only occur if the energy E of the incident free electron in the electron-ion center-of-mass (c.m.) frame matches the resonance condition $E = E_{\text{res}} = E_d - E_i$ where E_i and E_d are the total energies of all bound electrons in the initial and in the doubly excited state, respectively. Employing the principle of detailed

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balance the DC cross section can be calculated from the autoionization rate $A_a(d \rightarrow i)$ for a transition from the doubly excited state d to the initial state i :

$$\sigma^{(\text{DC})}(E) = S_0 \frac{g_d}{2g_i} \frac{1}{E} \frac{A_a(d \rightarrow i)\Gamma_d}{(E - E_{\text{res}})^2 + \Gamma_d^2/4} \quad (2)$$

with $S_0 = 7.88 \times 10^{-31} \text{cm}^2 \text{eV}^2 \text{s}$, statistical weights g_d and g_i and $\Gamma_d = \hbar [\sum_k A_a(d \rightarrow k) + \sum_{f'} A_r(d \rightarrow f')]$ denoting the total width of the doubly excited state d . The summation indices k and f' run over all states which from d can be either reached by autoionization or by radiative transitions with rates $A_a(d \rightarrow k)$ and $A_r(d \rightarrow f')$, respectively.

In the second step of reaction (1) the new charge state is stabilized by photon emission from the intermediate doubly excited state, thereby transferring the ion into a final state f below the first ionization limit. This radiative stabilization competes with autoionization which would transfer the ion back into its initial charge state with the net effect being resonant electron scattering. Accordingly, in order to obtain the cross section for DR one has to multiply the DC cross section from equation (2) by the branching ratio $[\sum_f A_r(d \rightarrow f)]/\Gamma_d$ for radiative stabilization. Integrating the resulting expression over the c. m. energy and assuming $\Gamma_d \ll E_{\text{res}}$ yields the DR resonance strength due to the intermediate state d in the isolated resonance approximation (Shore 1969), i.e.

$$\bar{\sigma}_d = S_0 \frac{g_d}{2g_i} \frac{2\pi}{E_{\text{res}}} \frac{A_a(d \rightarrow i) \sum_f A_r(d \rightarrow f)}{\sum_k A_a(d \rightarrow k) + \sum_{f'} A_r(d \rightarrow f')}. \quad (3)$$

In case of $\Delta n = 0$ DR of Li-like ions, i.e. for $1s^2 2s \rightarrow 1s^2 2p$ core excitations, the dominant decay channels of the doubly excited intermediate state (for very high n) can be identified as $2p_j n \ell \rightarrow 2s n \ell$ radiative and $2p_j n \ell \rightarrow 2s E_{\text{res}} \ell'$ autoionizing transitions with rates denoted as A_r and $A_{n\ell}$, respectively. Since the radiative transition only involves the excited core electron, its rate A_r to a good approximation is independent of the quantum numbers n and ℓ of the excited Rydberg electron. Neglecting all other transitions such as $2p_{3/2} n \ell \rightarrow 2p_{1/2} E' \ell'$ or $2p_j n \ell \rightarrow 2p_j n' \ell'$, equation (3) simplifies to

$$\bar{\sigma}_{n\ell} = (2j+1)(2\ell+1) S_0 \frac{\pi}{E_n} \frac{A_{n\ell} A_r}{A_{n\ell} + A_r} \approx (2j+1)(2\ell+1) S_0 \frac{\pi}{E_n} A_{<} \quad (4)$$

using the Rydberg resonance energy $E_{\text{res}} = E_n$, $g_d = 2(2j+1)(2\ell+1)$ and $g_i = 2$; in the r.h.s approximation $A_{<}$ denotes the lesser of A_r and $A_{n\ell}$. Autoionizing rates decrease as $\propto n^{-3}$ and even more rapidly with ℓ , such that at a given n the relation $A_{n\ell} > A_r$ holds only for $n\ell$ -Rydberg states with angular momentum ℓ below a limit ℓ_c . Thus $(\ell_c + 1)^2$ sublevels dominantly contribute to DR for a given core state j and consequently for the n -manifold $2p_j n \ell$ of doubly excited states the resonance strength is given as

$$\bar{\sigma}_n \approx (2j+1)[\ell_c(n) + 1]^2 S_0 \frac{\pi}{E_n} A_r. \quad (5)$$

Within this ‘counting of states’ picture the effect of external electric fields on DR is readily explained. In external electric fields Stark mixing of high- ℓ with low- ℓ levels occurs. This yields autoionization rates which are lower for low- ℓ and higher for high- ℓ

states as compared to the field free situation. The net effect is an increase of ℓ_c , i.e. an increase of the number of states participating in DR. Since high- n Rydberg states are more easily perturbed by external electric fields than low- n states the electric field induced enhancement of DR is stronger for higher- n $2p_j n \ell$ DR resonances.

This effect of external *electric* fields on DR was recognized early by Burgess and Summers (1969) and Jacobs *et al* (1976). Electric field enhancement of DR was subsequently found in numerous theoretical calculations (Hahn 1997). The first clear experimental verification of this effect has been given by Müller *et al* (1986) who investigated DR in the presence of external fields (DRF) of singly charged Mg^+ ions under controlled conditions. Further DRF experiments with multiply charged C^{3+} ions (Young *et al* 1994, Savin *et al* 1996) and Si^{11+} ions (Bartsch *et al* 1997) also revealed drastic DR rate enhancements by electric fields. Especially the Si^{11+} experiment which employed merged electron and ion beams at a heavy ion storage ring equipped with an electron cooler produced results with unprecedented accuracy, enabling a detailed comparison with theory. Whereas the overall agreement between experiment and theory as for the magnitude of the effect was fair, discrepancies remained in the functional dependence of the rate enhancement on the electric field strength (Bartsch *et al* 1997). This finding stimulated theoretical investigations of the role of the additional magnetic field which in storage ring DR experiments is always present, since it guides and confines the electron beam within the electron cooler. In a model calculation Robicheaux and Pindzola (1997) found that in a configuration of crossed \mathbf{E} and \mathbf{B} fields indeed the magnetic field through the mixing of m levels influences the rate enhancement generated by the electric field through the mixing of ℓ levels. More detailed calculations (Griffin *et al* 1998a, Robicheaux *et al* 1998) confirmed these results. It should be noted that in theoretical calculations by Huber and Bottcher (1980) no influence of a pure magnetic field ($\mathbf{E} = 0$) on DR was found up to at least $\mathbf{B} = 5$ T.

Inspired by these predictions we previously performed storage ring DRF experiments using Li-like Cl^{14+} ions and crossed \mathbf{E} and \mathbf{B} fields (Bartsch *et al* 1999) where we clearly discovered a distinct effect of the *magnetic* field strength on the magnitude of the \mathbf{E} -field enhanced DR rate. Shortly after that Klimenko and coworkers (1999) experimentally verified that for the m -mixing to occur the crossed \mathbf{E} and \mathbf{B} arrangement is essential. For the case of parallel \mathbf{B} and \mathbf{E} fields, where m remains a good quantum number, they did not observe any influence of the magnetic field on the measured recombination signal.

The aim of the present investigation with Li-like Ti^{19+} is to confirm the novel $\mathbf{E} \times \mathbf{B}$ field effect on DR for a heavier Li-like ion. Because of the strong scaling of the fine-structure splitting with the nuclear charge the $\text{Ti}^{18+}(1s^2 2p_{1/2} n \ell)$ and $\text{Ti}^{18+}(1s^2 2p_{3/2} n \ell)$ Rydberg series of DR resonances are well separated in energy. The corresponding series limits occur at 40.12 eV and 47.81 eV, respectively (Hinnov *et al* 1989). This energy difference is large enough that, in contrast to the Cl^{14+} experiment, here our experimental resolution permits to study the effect of external fields on both $\text{Ti}^{18+}(1s^2 2p_j n \ell)$ Rydberg series individually.

The experiments were carried out at the heavy ion storage ring TSR of the Max-Planck-Institut für Kernphysik in Heidelberg. Here we only give a brief account of the experimental procedure for DRF measurements. Details will be given in a forthcoming publication by Schippers *et al* (2000, and references therein) on DRF measurements with lithium-like Ni^{25+} ions.

Beams of $^{48}\text{Ti}^{19+}$ ions with intensities up to almost $80\ \mu\text{A}$ were stored in the ring at energies of $4.6\ \text{MeV/u}$. The ion beams were cooled by interaction with a velocity-matched cold beam of electrons which was confined by a magnetic field \mathbf{B} ; the direction of \mathbf{B} defines that of the electron beam. The electron beam diameter was $30\ \text{mm}$, while that of the cooled ion beam was of the order of $2\ \text{mm}$. First, as in the standard tuning procedure of the electron cooler, the electron beam was steered so that, along the straight interaction region of $1.5\ \text{m}$ length, the ion beam travelled on the electron beam center line and the guiding field \mathbf{B} pointed exactly along the ion beam; this minimized the electric field in the frame of the ions originating from space charge and motional ($\mathbf{v} \times \mathbf{B}$) fields. A reasonably ‘electric-field free’ measurement of the DR rate coefficient (with an estimated residual field of at most $\pm 10\ \text{V/cm}$) could then be obtained at high energy resolution by switching the energy of the electrons in the cooler to different values. The energy range thus covered in the center-of-mass frame includes all $\text{Ti}^{19+}(1s^2 2p_j n\ell)$ $\Delta n = 0$ DR resonances due to the $2s \rightarrow 2p_j$ core excitations. Recombined Ti^{18+} ions were magnetically separated from the parent Ti^{19+} beam and detected with an efficiency $\geq 95\%$ downbeam from the cooler behind the first bending magnet.

Controlled motional electric fields in the frame of the ions were then applied by superimposing in the interaction region a defined transverse (horizontal) magnetic field $B_x \ll B_z$ in addition to the unchanged longitudinal field B_z along the ion beam direction (z). This field was generated by the electron-beam steering coils along the complete straight section of the electron cooler and created a motional electric field $E_y = vB_x$ in the frame of the ions at a beam velocity v ; the total magnetic field strength $(B_x^2 + B_z^2)^{1/2}$, however, remained almost unchanged. Progressively different electric fields were produced by varying the transverse magnetic field strength B_x . At a given transverse field B_x the electron beam (following the magnetic field lines) and the ion beam are misaligned by the small angle B_x/B_z so that the distance of the ion beam from the center of the electron beam varies along the interaction region. This leads to unwanted effects due to the electron space charge: (I) a variation of the (temperature average) relative velocity between electrons and ions along the interaction path, resulting in a degraded energy resolution; (II) creation of an additional electric field E_x which, in contrast to the imposed field E_y , varies along the interaction region. Low electron densities were chosen in order to keep these effects small. With electron currents of $20\ \text{mA}$, measurements were performed at an electron density of $6.2 \times 10^6\ \text{cm}^{-3}$. The cooler was operated at longitudinal field strengths $B_z = 30, 41.8, 60.0$ and $80.1\ \text{mT}$. Transverse fields of $|B_x| \leq 0.7\ \text{mT}$ (measured with an uncertainty of $\pm 3\%$) were applied, corresponding to controlled motional electric fields $|E_y|$ up to $280\ \text{V/cm}$; in all measurements the misalignment angle was kept below $|B_x/B_z| \lesssim 0.02$. The ratio

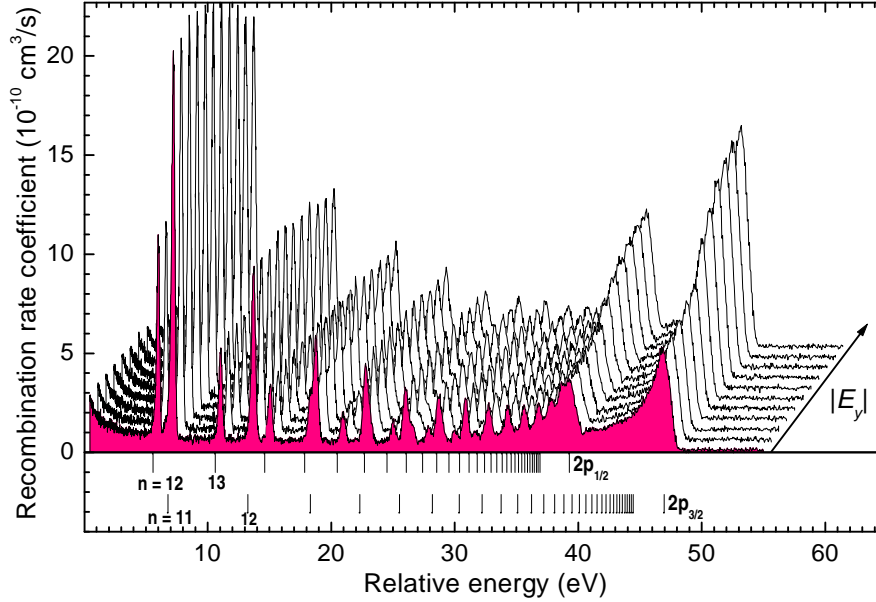


Figure 1. Absolute recombination rate coefficients measured for 4.6 MeV/u Ti^{19+} ions at applied motional electric fields $|E_y|$ increasing nearly linearly from 0 to 265 V/cm; longitudinal magnetic field $B_z=69$ mT, electron density $6 \times 10^6 \text{ cm}^{-3}$. Energetic positions of the $2p_{1/2} n\ell$ and $2p_{3/2} n\ell$ resonances according to the Rydberg formula are indicated.

E_x/E_y of the unwanted electric space charge field and the applied motional field is expected to vary linearly along the interaction region with $|E_x/E_y|$ remaining always below 0.07 for all measurements with different experimental parameters.

Before each energy scan with an imposed electric field E_y , ions were injected into the ring, accumulated and then cooled for 1 s. After that, the cathode potential of the cooler was offset from cooling by about 1 kV (corresponding to 55 eV in the center-of-mass frame) and then, the steering coils were set to produce a defined transverse magnetic field B_x . Next, the center-of-mass energy was ramped down from about 55 eV to 1 eV within 4 s thus completing a first mini-cycle. After new ion injection and cooling (at $B_x = 0$), the next magnetic steering field B_x (i.e., next E_y) was automatically set and a new energy scan started. The mini-cycles, covering one complete energy scan each, were repeated for a set of pre-chosen magnetic steering fields. A grand cycle through typically 11 values of $E_y = vB_x$ thus took about 2 minutes and such cycles were repeated until a satisfying level of statistical uncertainty (below 3% per channel) had been reached.

Sets of recombination rate measurements were made for different longitudinal fields B_z . Using measured beam currents the spectra were calibrated, reaching an uncertainty of $\pm 20\%$ for absolute and $\pm 5\%$ for relative rate coefficients. The center-of-mass energies were determined (with uncertainties below $\pm 1\%$) from the average relative velocities of electrons and ions, accounting for the angle between the electron and the ion beam due to the applied transverse field B_x .

A typical set of measurements is presented in figure 1 and shows the two series of Rydberg resonances converging to the $2p_{1/2}$ and $2p_{3/2}$ core excitation limits. A significant enhancement of the rate coefficient with increasing electric field E_y is observed for high Rydberg states $n \gtrsim 27$, while for the lower-lying resonances the rate coefficient remains constant.

The enhancement of the DR via high Rydberg states is quantified by extracting rate coefficients integrated over different energy regions of the measured spectra. The integrals $I_{1/2}(E_y, B_z)$ and $I_{3/2}(E_y, B_z)$ extend over the energy ranges 33.4–40.57 eV and 40.57–50 eV, respectively, and represent the high-Rydberg contributions of the $2p_{1/2}n\ell$ and $2p_{3/2}n\ell$ series of Rydberg resonances with $n \geq 27$. For normalization purposes we also monitor the integral I_0 (integration range 4–24 eV) comprising DR contributions from lower n . It should be noted that the maximum quantum number of Rydberg resonances contributing to the measured recombination rate is limited by field ionization in the charge analyzing dipole magnet. Taking into account also radiative decay of high Rydberg states on the way from the cooler to the dipole magnet, we estimate the maximum quantum number to be $n_c = 115$.

The high-Rydberg contributions $I_j(E_y, B_z)$ ($j = 1/2, 3/2$) monotonically increase with $|E_y|$, while the lower- n contribution $I_0(E_y, B_z)$ remains constant. In order to provide a quantity for the following discussion that is independent of the normalization of the individual spectra, we consider ratios I_j/I_0 of the high- n to the low- n contribution in a single DR spectrum. The electric-field enhancement factor

$$r_j(E_y, B_z) = C_j(B_z) \frac{I_j(E_y, B_z)}{I_0(E_y, B_z)} \quad (6)$$

then directly measures the influence of the external electric field on the DR rates via high Rydberg states. The constants $C_j(B_z)$ have been chosen such that fits to the data points (see below) yield $r_j^{(\text{fit})}(0, B_z) = 1.0$.

The field enhancement factors $r_{1/2}(E_y, B_z)$ and $r_{3/2}(E_y, B_z)$ found for different B_z are shown in figure 2 as a function of $|E_y|$. The enhancement factors turn out to be independent of the sign of E_y , as expected. The formula

$$r_j^{(\text{fit})}(E_y, B_z) = 1 + s_j(B_z) E_j(B_z) \{1 - \exp[-E_y/E_j(B_z)]\} \quad (7)$$

which we have fitted to the measured enhancement factors, provides a useful parameterization of our data. The parameters which have been varied during the fits (at fixed values of B_z) are the saturation field $E_j(B_z)$ and the initial slope $s_j(B_z)$; tangents to $r^{(\text{fit})}$ at $E_y = 0$, representing the initial slopes are also displayed in figure 2. We note that the $E_y = 0$ data points are slightly above the fitted lines. This is due to the fact that zero applied field $E_y = 0$ still implies a residual electric field $\lesssim 10$ V/cm so that the measured dependence of $r_j(E_y, B_z)$ near $E_y = 0$ is washed out to some extent. At higher electrical field strengths the measured data points drop below the (dashed) straight lines (cf. figure 2). This is an indication that the electric field effect is subject to saturation which occurs at higher electric field strength where the mixing of ℓ -levels

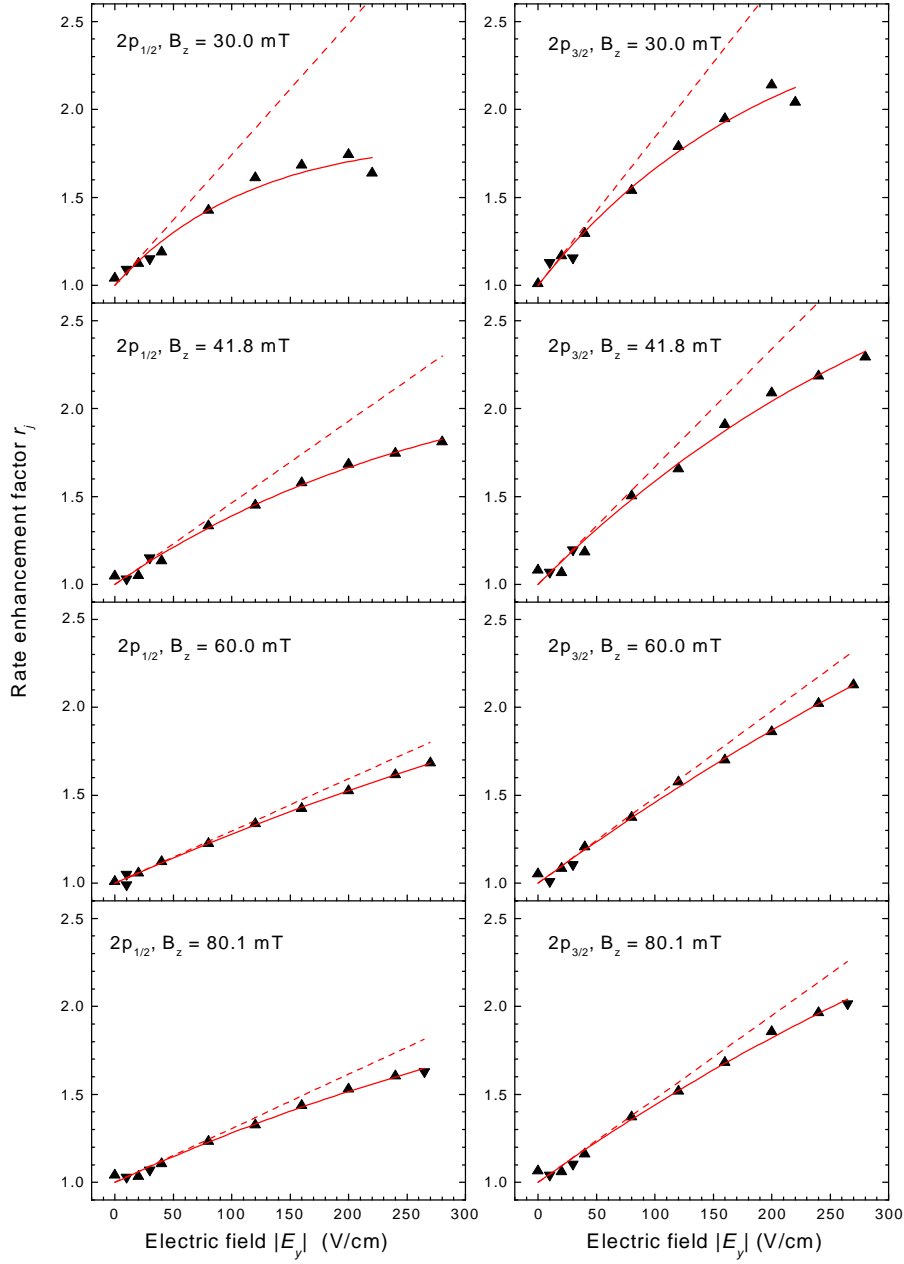


Figure 2. Measured field enhancement factors (cf. equation (6)) $r_{1/2}$ (left) and $r_{3/2}$ (right) as a function of the applied motional electric field strength $|E_y|$ for different longitudinal magnetic field strengths $B_z = 30.0, 41.8, 60.0$ and 80.1 mT (from top to bottom). Triangles pointing up (down) mark data points which have been measured with positive (negative) E_y . The full lines have been fitted to the data points (cf. equation (7)). The dashed straight lines are tangents to the fit at $E_y = 0$.

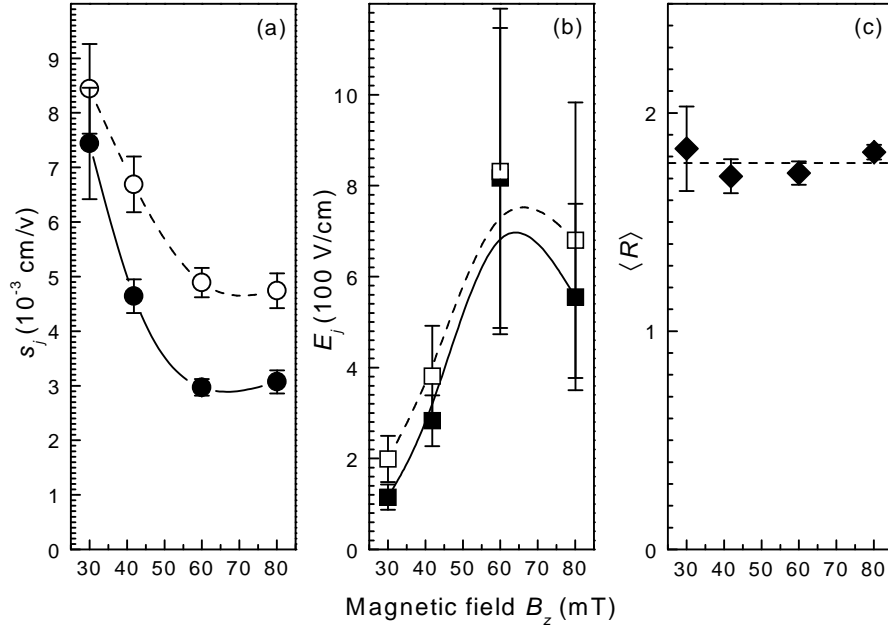


Figure 3. Dependence of the fit parameters (cf. equation (7)) $s_{1/2}$ (closed circles), $s_{3/2}$ (open circles), $E_{1/2}$ (closed squares) and $E_{3/2}$ (open squares) on the longitudinal magnetic field strength B_z . The error bars were obtained from the fits. The lines are drawn to guide the eye. The diamonds in panel (c) represent ratios R (cf. equation (8)) averaged over the electric field interval $80 \text{ V/cm} \leq |E_y| \leq 280 \text{ V/cm}$ as a function of B_z . The error bars correspond to one standard deviation. The dashed straight line represents the mean value 1.77 ± 0.06 .

is complete. Presently, higher electric fields are not accessible in our DR experiment. The fit parameter $E_j(B_z)$ indicates how fast the saturation regime will be reached.

The values for the parameters $s_j(B_z)$ and $E_j(B_z)$, which along with their uncertainties have been obtained from the fits, are displayed in figures 3a and 3b, respectively, as a function of the magnetic field B_z . Both s_j and E_j exhibit a strong dependence on the strength of the magnetic guiding field. The slopes s_j decrease with increasing magnetic field both for the $2p_{1/2}$ and $2p_{3/2}$ series of Rydberg resonances. This confirms our recent finding for Cl^{14+} ions (Bartsch *et al* 1999) where the existence of a sensitivity of DR to external *magnetic* fields in an $\mathbf{E} \times \mathbf{B}$ field configuration was experimentally demonstrated for the first time. The parameters E_j increase with increasing magnetic field strength, i.e. at higher B_z the saturation regime will be reached at higher electric fields $|E_y|$.

While the parameters E_j are not markedly different for the $2p_{1/2}$ and $2p_{3/2}$ series, the slopes $s_{3/2}$ are steeper than the slopes $s_{1/2}$ (open and closed circles in figure 3a, respectively), i.e. the relative increase of the DR line strength is stronger for the $2p_{3/2}$ series of Rydberg resonances than for the $2p_{1/2}$ series. For a comparison to recent theoretical predictions (Griffin *et al* 1998a, 1998b) we consider the ratio

$$R(E_y, B_z) = \frac{I_{3/2}(E_y, B_z) - I_{3/2}(0, B_z)}{I_{1/2}(E_y, B_z) - I_{1/2}(0, B_z)} \quad (8)$$

of absolute E_y induced DR rate enhancements for the $2p_{3/2}$ and $2p_{1/2}$ series of Rydberg resonances, which is practically independent of the integration ranges used for the determination of $I_{1/2}$ and $I_{3/2}$ as long as they cover nearly all DR resonances affected by the external fields. As a function of E_y the ratio R rises up to $|E_y| = 80$ V/cm and then essentially stays constant at higher electric fields. Values $\langle R \rangle$ averaged over the interval $80 \text{ V/cm} \leq |E_y| \leq 280 \text{ V/cm}$ are plotted in figure 3c which shows that $\langle R \rangle = 1.77 \pm 0.06$ independent of B_z .

In view of the fact that for a given n the manifold of $2p_{3/2}n\ell$ resonances contains twice as many sublevels that can be mixed by external fields as the manifold of $2p_{1/2}n\ell$ resonances ($8n^2$ vs. $4n^2$, cf. equation (4)) one expects a value of 2 for the ratio $\langle R \rangle$. We here observe a ratio somewhat lower than 2 similar to the value $\langle R \rangle \sim 1.5$ found in our experiments with lithium-like Ni^{25+} ions (Schippers *et al* 2000). In calculations for lithium-like Si^{11+} ions (Griffin *et al* 1998a) and C^{3+} ions (Griffin *et al* 1998b) ratios even less than 1 have been found. This has been attributed to the electrostatic quadrupole-quadrupole interaction between the $2p$ and the $n\ell$ Rydberg electron in the intermediate doubly excited state, which more effectively lifts the degeneracy between the $2p_{3/2}n\ell$ than between the $2p_{1/2}n\ell$ levels. Our experimental results suggest that this effect might be weaker than theoretically predicted.

Our data emphasize the relevance of the effect of small magnetic fields on DR via high Rydberg levels in conjunction with the well-known electric-field enhancement. This result bears important implications upon the charge state balance of ions in astrophysical and laboratory plasmas where both, electric and magnetic fields are ubiquitous.

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